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Satellite remote sensing, biodiversity research and conservation of the future

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Introduction

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Assessing and predicting ecosystem responses to global environmental change and its impacts on human well-being are high priority targets for the scientific community. The potential for synergies between remote sensing science and ecology, especially satellite remote sensing and conservation biology, has been highlighted by many in the past. Yet, the two research communities have only recently begun to coordinate their agendas. Such synchronization is the key to improving the potential for satellite data effectively to support future environmental management decision-making processes. With this themed issue, we aim to illustrate how integrating remote sensing into ecological research promotes a better understanding of the mechanisms shaping current changes in biodiversity patterns and improves conservation efforts. Added benefits include fostering innovation, generating new research directions in both disciplines and the development of new satellite remote sensing products.

1. Introduction

Fifty years ago, the world's imagination was captured by the space race, and the prospect that, one day, humans would walk on the moon and plan a mission to Mars. As decades have gone by, however, scientific and political attention has slowly shifted to making sure our Earth continues to be a hospitable place for future generations to prosper. Human activities are indeed threatening to breach planetary boundaries through climate change, changes in land use, the release of nitrogen and phosphorus into the environment, freshwater extraction and diversion, ocean acidification and ozone depletion, among others [1]. With one in every 10 000 species estimated to be lost per year, the current rapid rate of biodiversity loss is of particular concern [2], given the mounting evidence linking levels of biodiversity, delivery of essential ecosystem services and human well-being [3,4].

Conservation biology has been historically tasked with coordinating research and monitoring efforts to revert the current biodiversity crisis [5]. Being rooted in ecology, the discipline has traditionally sought relevant information from ground-based methodologies. The roots of environmental remote sensing, on the other hand, lie in the disciplines of geography and engineering (e.g. [6]). Interestingly, biodiversity and environment are concepts that possess a large degree of overlap: a number of the features describing an environment are indeed components of biodiversity. Abiotic environmental conditions (i.e. climatic conditions, roads and building distributions or sea surface temperature) are then key drivers of changes in biological diversity, making the monitoring of these features extremely relevant to ecologists and conservation biologists alike [7,8]. Conservation biology and geography are, moreover, disciplines that have partially converging aims: environmental geography, for example, is a branch of the discipline that examines the relationship between human beings and the natural world [9]; such knowledge is the key to developing effective conservation strategies [10]. Given this level of common interests, there should be much potential for interdisciplinary work between remote sensing and ecology to trigger innovative approaches and new research directions in both disciplines, while supporting the development of new remote sensing products.

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The potential for synergies between biodiversity- and conservation-focused research and remote sensing has actually been acknowledged by both disciplines for some time (e.g. [11–15]), and there exists a clear interest among researchers, practitioners and data providers to better understand how remote sensing can benefit biodiversity research and conservation. Nowadays, it is indeed not unusual to discover a symposium on the applications of satellite data to ecology in meetings such as the International Mammal Conference, the Society for Conservation Biology or the Ecological Society of America. Likewise, symposia highlighting the conservation relevance of remote sensing approaches are not uncommon at remote sensing conferences such as the International Symposium for Remote Sensing of Environment or the International Society for Optics and Photonics. However, the research presented at such events is often conducted *within* each community and therefore not in a fully interdisciplinary manner. Similarly, the development of new remote sensing products and the creation of new ecological sampling tools and methods are very rarely executed in concert. Collaborative projects aiming to develop products specifically matching the scientific interests of both communities are not the norm. For example, the remote sensing community has traditionally been seen as uni-directionally providing data to support ecological research and conservation efforts [16]. Yet, such collaborative, integrated approaches are likely to be key if we are to realize the full potential for satellite data to support future environmental management decision-making.

With this introduction to our special issue entitled 'Satellite Remote Sensing for Biodiversity Research and Conservation Applications', we aim to offer an interdisciplinary perspective on the future prospects of satellite remote sensing for biodiversity research and conservation. We briefly present some of the challenges associated with developing integrative approaches and conclude with an overview of the scope of each of the contributions included in this issue.

2. A road paved with challenges

Pressing challenges affecting our home planet at a global scale emphasize the need for observations of the Earth from space [17]. Space offers a truly global perspective for observing changes in the environment in which we live and upon which we depend. For decades, space-based observations of Earth have provided an increasingly powerful understanding of weather and climate, along with other geophysical phenomena [18]. In doing so, they have enabled longer term and more accurate forecasts of changes in the physical and chemical processes of our planet. A growing body of literature, moreover, demonstrates the power of space-based observations for tracking and modelling changes in elements of biodiversity and in supporting its conservation and management (e.g. [19–23]). Ground-based methodologies are indeed difficult to use for mapping and predicting regional or global changes in the distribution of biodiversity, something that is at the core of many national and international conservation agendas [24]. Satellite remote sensing, on the other hand, offers a relatively inexpensive and verifiable means of deriving complete spatial coverage of environmental information for large or remote areas [7,12].

There is little doubt that satellite remote sensing can make a difference in biodiversity monitoring and conservation, and this potential is likely to be best achieved when effective collaborations between experts in remote sensing and experts in biodiversity monitoring and conservation are being developed. Such collaborative work is, however, still rare, for a number of reasons. One reason arises from the lack of a shared interdisciplinary space to facilitate collaboration between communities. With remote sensing generally located in social sciences or engineering departments and ecology falling under life sciences, students and staff from each community are very quickly spatially segregated within academia, reducing potential interactions. Likewise, few conferences and peer-reviewed journals reach both communities equally. Any interdisciplinary work requires good communication between the parties involved, and communication relies on a common understanding of relevant concepts [25]. All parties also need to be able to understand the constraints shaping the datasets considered, as well as the possible errors propagated in subsequent analyses. Yet, ecology trainees are, for example, rarely exposed to words such as 'multispectral', 'radiometer' or 'atmospheric corrections', while remote sensing experts often struggle when confronted with concepts such as 'ecological niche', 'life history' or 'species evenness'. Another issue lies in the different resolutions at which the two communities typically work. Remote sensing experts are used to dealing with very large areas, with spatial resolutions typically ranging from tens of metres to several kilometres, and temporal resolutions between daily and decadal. Ecologists, on the other hand, often deal with relatively smaller areas at spatial resolutions of a few metres and temporal resolutions that tend to be either daily or annual [26]. This lack of common reference frames can seriously hamper collaborative work.

Data and algorithms' accessibility might be another reason preventing the emergence of more collaboration between the remote sensing and ecology communities. Access to many remote sensing products still is not free of charge [27], while only a small fraction of ecological data ever collected is readily discoverable and accessible, much less usable [28]. There are also several logistical and technical challenges associated with the storage, sharing, manipulation and analysis of the datasets of common interest to both communities [29]. Ecological datasets are indeed becoming large, with sequencing systems, for example, generating records of millions or even billions of base pairs in a single session; or citizen science programs producing massive quantities of data (e.g. [30,31]). Similarly, space-borne remote sensing instruments can sometimes collect information for the whole world on a daily basis [18]. Each community then stores its information in different databases and archives, and the data stored therein exist in different formats (e.g. spreadsheets versus pixels), subjecting the integration of datasets across the two communities to significant processing and information technology hurdles. Combining remote sensing and ecological datasets for visual inspection or analysis can, moreover, require sophisticated algorithms and software, as well as significant computing resources, which might not be readily available for either community. Data sharing and transfer also become difficult in such cases, especially for users in developing countries where access to broadband internet can be reduced. Altogether, this can create a situation where partners do not have the same level of opportunities to contribute to the project, sometimes leading to partners' disengagement and the failure of the collaboration.

A final challenge to the emergence of effective interdisciplinary work resides in defining research objectives that are rewarding and considered scientifically valuable by members of both disciplines. For both communities to engage actively in research topics requiring the combination of their skills and knowledge, the aims and outputs of the work should indeed contribute and enrich both remote sensing and ecology [32]. These outputs should be recognized by both communities as being significant achievements in their fields, for scientists to reap the benefits of the time and effort they invest in a project, but also for funding agencies to increase their support towards such collaborative activities.

3. Bridging gaps between ecological research and remote sensing

A higher level of interdisciplinary work between remote sensing experts and ecologists has the potential to help us tackle many environmental challenges, while creating numerous opportunities for the advancement of both disciplines. To reach this potential, better and stronger communication channels are needed for these communities to start developing a better coordinated, more effective research agenda. Scientific platforms enabling information transfer and networking opportunities, such as the Group on Earth Observations Biodiversity Observation Network or the group on Remote Sensing for Biodiversity within the Committee on Earth Observation Satellites (CEOS), need to continue and expand their impacts, while user-friendly, intuitive and centralized data and algorithms portals need to be developed to further enhance communication and promote joint use of the different types of tools and data products [33]. In particular, knowledge transfer between communities can be enhanced by increasing efforts to reduce complicated terminology and detail software, packages, algorithms and raw data used within publications.

Training opportunities that help set common references across communities are still extremely rare, and this lack of opportunities hampers the emergence of a new generation of scientists who are able to carry out integrated, multidisciplinary approaches. To address this shortcoming, the biodiversity and remote sensing communities should seek to develop joint undergraduate and postgraduate programmes. They should, moreover, seek to increase access to free tools, both in terms of open-source software development, but also in terms of increased training opportunities focusing on the use of these free tools [22]. More broadly, capacity building within the ecology and conservation communities would address many of the barriers related to limited skills, lack of knowledge and software/data access and usability, ultimately promoting dialogue and the development of initiatives actively engaging both communities [34]. In addition, it is perhaps time for a new society and associated journals specifically dedicated to bridging these gaps in training, terminology and understanding.

Better ways of linking *in situ* ground- or water-based efforts with remote sensing initiatives are crucial to overcoming the challenge of scale currently separating the communities. These may include increased efforts to share more widely existing biodiversity data via web interfaces (Movebank, Smithsonian Wild, Map of Life, etc.) or developing means for recognizing and rewarding those making their data available, for instance, by citing the authors or creators of datasets in scientific journals [28]. While doing so will be challenging given the wide array of entities surveying biodiversity, starting at a high level with some of the larger biodiversity information providers, such as the International Union for the Conservation of Nature and the Global Biodiversity Information Facility, seems a realistic first step. The development of citizen science approaches to collect environmental reference information and biodiversity data simultaneously also has the outstanding potential to ease the integration of coarser-scale remotely sensed data of environmental parameters with countless fine-scale *in situ* observations of biodiversity elements [35,36].

4. Satellite remote sensing for biodiversity research and conservation applications

With this special issue, our purpose is to demonstrate how integrative approaches that involve active knowledge transfer between the remote sensing and ecological communities result in synergies that lead to a better understanding of the mechanisms shaping current changes in biodiversity patterns. This in turn increases our ability effectively to anticipate and mitigate adverse consequences to human well-being. In essence, these papers document a new and growing partnership between two communities that are just beginning to appreciate the needs and capabilities of each other. Our compilation of case studies brings together a range of stakeholders, spanning academic experts in remote sensing and ecology, through conservation NGOs, to policy makers and space agency representatives. By presenting new approaches and discussing future development directions, we hope this special issue will help to shape future common research activities.

A number of the contributions within this issue represent the outcome of a workshop funded through the German Space Agency (DLR), with the support of CEOS, aimed at sparking new collaborative work between the remote sensing and conservation communities. During this workshop, which took place in Munich in October 2012, participants were paired across disciplinary boundaries and asked to develop novel research projects, which would not be feasible without a deeply integrative approach that combined expertise from both fields. Other contributions have been solicited from investigators associated with the National Aeronautics and Space Administration (NASA) Biodiversity and Ecological Forecasting programs and working at the interface between biodiversity research and remote sensing.

To bring structure to our compilation of case studies, the issue has been organized with respect to the 'Pressure-State-Response' framework adopted by the Convention on Biological Diversity [37]. Contributions have therefore been selected based on their relevance to discussions on the utility of remote sensing to track the extent and intensity of the threats to biodiversity (commonly referred to as 'pressures' on the natural world), to monitor the 'state' of biodiversity, and to detect the consequences of the implementation of policies or actions aimed at preventing or reducing biodiversity loss (commonly referred to as 'responses'). Admittedly, remote sensing includes a wide range of technologies (ranging from airborne sensors to satellite-based information, global positioning systems and camera traps), which cannot all be covered in a comprehensive manner in a single issue. We have therefore decided to focus our proposal on satellite-based information only.

Habitat loss and degradation as well as invasive alien species are among the most important threats to biological diversity, and the first section of this special issue provides three examples of how remote sensing can help detect and model the evolution of these threats. The contribution by Duncan *et al.* [38] assesses the potential for Landsat imagery to detect and map anthropogenic disturbances in desert environments, focusing on oil exploration in the Sahara as a case study. Then Clark *et al.* [39] examine the current and projected regional distributions of an invasive species in the United States, *Ailanthus altissima* (the tree-of-heaven), integrating ground-based measurements from the United States Forest Service's Forest Inventory and Analysis program with new data products from NASA's Terrestrial Observation and Prediction System. The third contribution, by Wegmann *et al.* [40], assesses habitat change within each African protected area and measures the contribution of each of these protected areas to the connectivity of the global protected area network.

Biodiversity is defined as the natural variety and variability within and among living organisms and the ecological complexes in which they naturally occur, as well as the ways in which organisms interact with each other and with the physical environment [41]. Biodiversity is a multidimensional concept that includes different components (e.g. the genetic, population, species and community levels), and each of them has compositional, structural and functional attributes (e.g. population size, species composition and allelic distribution). The second section aims to demonstrate how satellite-based data can provide relevant information on the distribution of genetic variation; on the distribution and performance of particular species and on the distribution of species richness and communities. The contribution by St Louis *et al.* [42], compares the ability of two measures derived from unclassified remotely sensed data, a measure of habitat heterogeneity and a measure of habitat composition, to capture the variability in bird species richness and the spatial distribution of 10 species in a semi-arid landscape of New Mexico. Madritch *et al.* [43] demonstrate the capacity of imaging spectroscopy to discriminate among genotypes of *Populus tremuloides* (trembling aspen), one of the most genetically diverse and widespread forest species in North America, whilst Hurley *et al.* [44] use information on weather, vegetation types, snow cover and vegetation productivity to model the body mass and survival of mule deer fawns, using information collected from 1998 to 2009 on more than 1500 individuals dispatched across 10 different population units. This allows the authors to identify, for the first time, key periods for the determination of these important drivers of ungulate population dynamics. The last contribution in this section, by Dodge *et al.* [45], provides new insights on how changes in environmental conditions may affect the energy budget of long-distance migrating birds, using nearly 10 years of data from tagged *Cathartes aura* (Turkey vultures) in three populations in North America and one population is South America.

One of the most common responses to changes in biodiversity levels is the setting and/or enhanced management of protected areas [46], a response that can be informed by remote sensing data. In this final section, the contribution by Di Marco *et al.* [47] aim to illustrate this point and combine information on trends in species extinction risk, levels of conservation action and land cover to assess the contribution of protected areas to improvements in biodiversity conservation in Africa.

As demonstrated in this special issue, satellite remote sensing can tell us much about the condition of biodiversity and the potential for conservation interventions across multiple spatial and temporal scales. Good work is taking place, but much more is required given the current pace of change in environments around the world. Integration and collaboration across disciplinary lines are the keys to a brighter future for both communities—and the planet that they share.

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